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(54) Title: MULTICOLOR LIGHT EMITTING DIODE, METHODS FOR PRODUCING SAME AND MULTICOLOR DISPLAY INCORPORATING AN ARRAY OF SUCH LEDs

(57) Abstract

A multicolor LED structure is composed of a stacked vertical structure of individual double heterostructure (DH) LEDs of III-V semiconductor compounds emitting light in different colors. The application of separate voltages to each LED enables the control of the relative intensities of emitted light from the LEDs. The multicolor structure includes three LEDs, one red, one blue and one green LED, enabling a full color display by providing a two-dimensional array of elements of these multicolor LEDs, the elements' colors controlled in accordance with a time variant multicolor display signal, such as a color video signal.

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Multicolor light emitting diode, methods for producing same and multicolor display incorporating an array of such LEDs.

This invention relates to light emitting diodes (LEDs), and more particularly to multicolor LEDs of III-V compounds, and to color display devices incorporating arrays of such LEDs.

Red, orange and yellow LEDs have existed for some time and have found widespread commercial use, notably in electronic displays. The recent reports of yellow, green and blue emitting LEDs holds out the promise of full color gamut displays incorporating such LEDs.

Various schemes are employed currently to achieve full color displays. The most ubiquitous example is the color cathode ray tube, which employs an array of triads of red, blue and green phosphor elements (usually in the form of vertically oriented stripes), which is repetitively scanned by three electron beams carrying respectively the red, blue and green components of a color (video or data/graphic) display image. Another common example is the color liquid crystal display (LCD), in which an x,y matrix of triads of LC pixels are addressed repetitively. In such an LCD device, the component colors red, blue and green of the color image are obtained by the use of color filters of the appropriate color on the pixels in each triad.

In operation of the LCD, the red, blue and green components of the color display image are separately imaged, at a high rate such that the observer cannot distinguish between the separate fields of color, but instead integrate these fields into a full color display image.

A disadvantage of such systems is that image resolution is limited by the spatial separation of the pixels making up the individual triads, and the spatial separation of the triads from one another in the array. In the case of CRTs, a further disadvantage is the need for high voltage. In the case of LCDs, a further disadvantage is that the color filters reduce the light efficiency of the system.

Japanese patent 7015044 describes a multicolor LED composed of two or three different color LEDs arranged together and sealed into a single mold.

Japanese patent 7183576 describes a multicolor LED structure of stacked GaN compound semiconductor LED's, which is said to provide color mixing on a single chip.

An object of the invention is to provide a color display which overcomes at least some of the disadvantages of prior art color displays employing separate pixels for each of the component colors of the system.

Another object of the invention is to provide a color display in which more than one and preferably all of the component colors of a full color image can be emitted by a single pixel element.

Another object of the invention is to provide a color display in which such a multicolor pixel element is achieved without the use of filters.

Another object of the invention is to provide a color display which does not require high voltage for its operation.

Another object of the invention is to provide a multicolor LED for use in such a display.

Another object of the invention is to provide such a multicolor LED composed of a stack of GaN compound semiconductor double heterostructure (DH) LED's.

In accordance with one aspect of the invention, a multicolor LED is provided in the form of a stacked layer structure of three separate double heterostructure (DH) LEDs, each emitting light of a different color, the LEDs preferably arranged in the sequence: n-p, p-n, n-p; or p-n, n-p, p-n, the LED's comprised of epitaxially grown layers of III-V compounds designed with intrinsic, p or n active layers to emit light in different regions of the visible spectrum and in the form of a wedding cake structure.

The relative intensity of each color is controlled by applying individual voltages to each LED through an external bias. By controlling these individual voltages, primary colors can be mixed to achieve any color within the gamut of the primary colors from the single stacked layer structure of individual LEDs.

In accordance with a preferred embodiment of the invention, the stacked structure of three LEDs is achieved in a multilayer vertically oriented stack of $In_xAl_yGa_{1-x-y}N$ layers epitaxially grown on a single crystal substrate, in the sequence n-i-p, p-i-n, n-i-p, where the i-active layer has the composition and/or the dopant needed to achieve the desired emission color for each LED. For example, by varying the amount of In to vary the bandgap, and/or by varying the doping level of dopants such as Zn or Cd to introduce recombination centers in the gap, light emissions peaking at the desired wavelength region can be obtained.

The device may be grown on sapphire, SiC, ZnO or other suitable, and preferably transparent, single crystal substrate. Conventional photolithographic processing

steps including masking, chemical vapor deposition such as MOCVD, MBE, etching, ion implanting and metallizing may be used to fabricate the LED structures.

In accordance with another aspect of the invention, a multicolor display is provided, comprising an array of multicolor LED structures of the invention. In such a multicolor display, all pixels can be driven in parallel by a dc voltage, without the need for color filters or a high voltage power supply. In addition, such a display is capable of having higher resolution than current display devices based on phosphor or LC technology, in which the different colors are emitted from spatially separated red, green and blue pixels.

Brief description of the drawing:

Fig. 1 is a cross-section of one embodiment of a multicolor LED structure of the invention, comprising a stack of epitaxially grown and selectively etched III-V layers, and implanted confinement layers;

Fig. 2 is a cross-section of another embodiment of a multicolor LED structure of the invention, comprising a stack of epitaxially grown and selectively etched III-V layers, including confinement layers;

Figs. 3(a) through (f) are cross-sections illustrating the step-by-step fabrication of the LED structure of Fig. 2;

Figs. 4(a) through 4(d) are schematic illustrations of another technique for the step-by-step fabrication of the LED structures of Figs. 1 and 2;

Fig. 5 is a circuit diagram illustrating one embodiment of a circuit for driving the multicolor LED structure of the invention;

Fig. 6 is a cross section of a portion of a multicolor LED structure similar to that of Fig. 1, having switches for controlling the application of driving voltages in accordance with the circuit of Fig. 5; and

Fig. 7 is a schematic diagram of a color display comprising a two dimensional array of multicolor LED structures of the invention.

Referring now to Fig. 1 in more detail, there is shown in cross section one embodiment of a stacked epi layer multicolor LED structure 10 of the invention. Single crystal substrate 12 is chosen to have a lattice constant suitable for matching to those of the epi layers through one or more buffer layers. Examples of suitable single crystal substrate materials are alumina (sapphire), silicon carbide and zinc oxide.

This multilayer structure may be grown by any suitable epitaxial growth

technique, such MOCVD or MBE. Growth of epitaxial layers of $In_xAl_yGa_{1-x-y}N$ in accordance with the MOCVD technique can be carried out using ammonia (NH_3), trimethyl gallium (TMG), trimethyl aluminum (TMA), and trimethyl indium (TMI) at a growth temperature within the range of 700-1050C. Bi-cyclopentadienyl magnesium (Cp_2Mg) can be used for Mg doping, diethyl zinc (DEZ) for Zn doping, and monosilane (SiH_4) for Si donor doping.

In accordance with conventional practice, a buffer layer 14 of n+ GaN is grown on the surface of the substrate 12 in order to improve the structural quality of the subsequently grown epi layers. This buffer layer also serves as an electrical contact layer for the first LED structure, and for this purpose is made n+ by doping with Si or other suitable dopant in the known manner.

The next epi layer 22 is the first layer of the red-emitting diode 16. Layer 22 has the composition $Al_yGa_{1-y}N$, where y is for example 0.2, and is doped n, i.e., to a higher level, resulting in a conductivity level less than that of the buffer layer underneath. This layer 22 is the first cladding layer for the next layer 24, which is the active or light emitting layer. The thickness of the cladding layers may be from 200 up to 5000 Angstroms in thickness.

Layer 24 is $In_xGa_{1-x}N$:Zn, and is essentially electrically insulating. The thickness of the active layers in this structure is from 15 up to 300 Angstroms, above which strain and defects become excessive.

The next layer 26 is the second, p-type, cladding layer of $Al_yGa_{1-y}N$, having essentially the same composition as the n-type cladding layer 22, but doped with Mg to result in a p-type conductivity.

The final layer of the red emitting LED 16 is layer 28, having the composition GaN and being doped p+ with Mg to act as a common electrical contact layer for the red-emitting LED 16 and the green-emitting LED 18.

Layer 30, the first layer of the green-emitting LED 18, has the composition $Al_xGa_{1-x}N$, and is doped p-type. This is the first cladding layer for active layer 32, which has the composition $In_xGa_{1-x}N$:Zn, and is essentially electrically insulating.

The next layer 34 is the second, n-type cladding layer having a composition n-$Al_yGa_{1-y}N$, and doped with Si.

The final layer of the green LED structure 18 is n+ GaN layer 36, which acts as a common electrical contact layer for the green LED structure 18 and the final, blue emitting LED structure 20. This layer is also doped with Si.

The blue emitting LED structure consists of n $Al_xGa_{1-x}N$ cladding layer

38, $In_xGa_{1-x}N$:Zn active layer 40, p $Al_yGa_{1-y}N$ cladding layer 42, and a final p+ GaN contact layer 44. Atop this layer 44 is a thin, semi transparent metal electrode layer 62 of Ni/Au alloy or other suitable electrode material.

The contact layers of GaN are doped with either Mg or Si to achieve p or n type conductivity, in the known manner. Typical doping levels are used to achieve carrier concentrations of 10^{19} - 10^{20}/cubic centimeter, resulting in a conductivity of about 1/ohm-cm. for p type, and 10^{13}/cubic centimeter, resulting in a conductivity of about 10^3/ohm-cm. for n type. The cladding layers of $Al_yGa_{1-y}N$, where x is for example, 0.2, are also doped with either Mg or Si to achieve p type or n type conductivity. Typical doping levels are used to achieve carrier concentrations of 10^{13} - 10^{17}/cubic centimeter, resulting in a conductivity of about $2x10^{-1}$/ohm-cm. for the p type layers, and $5x10^{17}$/cubic centimeter, resulting in a conductivity of about 10^2/ohm-cm. for the n type layers.

The active layers all have the composition $In_xGa_{1-x}N$:Zn, having a value of x up to 1.0, chosen to achieve a band gap suitable for the emission of the desired wavelength of light, for example, about 1.0 for red emission, about 0.45 for green emission and in the range of about 0.15-0.25 for blue emission. See K. Osamura et al, Solid State Comm., Vol. 11, 617 (1972). As is known, emission wavelength of the active layer can also be controlled through Zn doping. See in this regard H. Amano et al., J. Crystal Growth 93 (1988) 79-82, and J. Pankove, Mat. Res. Soc. Symp. Proc., Materials Res. Soc., vol. 162, p. 520.

The LED structures 16, 18 and 20 are preferably cylindrically shaped, i.e., circular in plan view, and arranged concentrically. This results in the stepped or "wedding cake" structure shown in the section view of Fig. 1. As will be readily appreciated, this structure may be achieved by first growing the epi layers in succession, and then carrying out a series of masking and etching steps using conventional photoresist and etching materials and techniques to define the individual LEDs.

An exemplary method comprises the steps of:

(a) forming the layers corresponding to the individual LEDs sequentially on a substrate to form a multilayer structure;

(b) forming an etchant mask on the top surface of the multilayer structure;

(c) removing the exposed portions of the layers corresponding to the top-most LED by etching, to define the top-most LED;

(d) removing the etchant mask; and

(e) repeating the above steps for each of the succeeding LED structures, with the etchant mask for each repetition being progressively larger than that of the

preceding mask, whereby the succeeding LED structures are progressly larger than the preceding LED structure.

The resultant stepped structure enables the convenience of depositing electrodes for each LED on the exposed portion of its top surface. Thus, as shown in Fig. 1, electrode 48 is formed on the top of red LED 16 and electrode 50 is formed on the top of green LED 18. Exemplary materials for forming the electrodes are Au/Ni alloy for contact to the p-type layers and Al or a Ti/Al alloy for contact to the n-type layers. A common ground electrode 46 for the entire structure is formed on the buffer layer 14.

The final electrode for the blue LED is a thin (100-300 Angstroms) semi-transparent layer of for example a Ni/Au alloy. This layer allows the collection of light from the top of the multilayer multicolor LED structure. Alternatively, the use of a transparent substrate such as sapphire would allow the collection of light from the bottom of the structure. Such light collection may be enhanced by the formation of a mirror on the side of the multicolor LED structure opposite the transparent side.

The structure just described results in an integrated vertical stack of three double heterostructure (DH) LEDs, with the sequence from substrate to top of: n-i-p (red); p-i-n (green); and n-i-p (blue). The relative intensity of these colors is controlled by external voltages applied to the individual LEDs of the structure, allowing for the "mixing" of the primary colors to achieve any arbitrary color from a single multicolor LED structure. A two dimensional array of such LED structures, in which the combined color output of each LED structure or pixel is controlled independently in a time variant manner in accordance with an applied signal, for example, a video signal, results in a full color display. Each pixel in the display can be scaled down to a size on the order of a few microns, using well known photolithographic techniques employed in the fabrication of integrated circuits.

In order to increase the efficiency of the LED structure, the active areas of the red and blue LEDs can be confined by forming high resistivity current blocking regions. Four such regions 56, 58, 60 and 62 are shown in Fig. 1. These regions are formed by ion implantation of a dopant such as oxygen or hydrogen to a resistivity of the order of 10^{-2} ohm-cm, in the known manner.

Alternatively, current blocking regions could be formed by the growth of separate layers of opposite conductivity type to create reverse biased p-n junction barriers to the majority carriers. A multicolor LED structure having such current blocking layers is shown in cross section in Fig. 2, and the sequence of processing stages to arrive at the

structure of Fig. 2 is illustrated in Figs. 3(a) through 3(f).

Beginning at Fig. 3(a) with a substrate 70, a buffer layer 72 of n+ GaN is grown on the substrate, after which the first three layers of a red LED structure are formed, in the order of: n-AlGaN cladding layer 80, InGaN:Zn active layer 82 and p-AlGaN cladding layer 84. Then, a current blocking layer 86 of n-AlGaN is formed. Next, a portion of current blocking layer 86 is removed by masking and selective etching, to result in the structure shown in Fig. 3(b).

Next, the contact layer 88 of p+GaN is formed, followed by the layers of the green LED, including the first cladding layer 90 of p-AlGaN, the active layer 92 of InGaN:Zn, and the second cladding layer 94 of n-AlGaN. A second blocking layer 96 of p-AlGaN is then formed on the green LED structure, as shown in Fig. 3(c), and a portion of this blocking layer is removed by etching, resulting in the structure shown in Fig. 3(d).

Next, the contact layer 98 of n+GaN between the green and the blue LEDs is formed, followed by the layers of the blue LED, including first cladding layer 100 of n-AlGaN, active layer 102 of InGaN:Zn, and second cladding layer 104 of p-AlGaN. Finally, contact layer 106 of p+ GaN, as shown in Fig. 3(e).

Next, using a series of masking and etching steps, outer portions of the layers are removed to define the wedding cake structure, in which the green LED is smaller than the red LED and the blue LED is smaller than the green LED, as shown in Fig. 3(f).

As an alternative to the above described technique of first forming all of the layers of the multicolor LED structure, and then masking and back-etching to define each of the individual LEDs, thereby to form the wedding cake structure, the areas to be occupied by the LEDs can instead be defined initially by first depositing a mask of a material having a poor sticking coefficient such as SiO_2, forming an aperture in the mask to define the area of the first LED to be formed, forming the first LED structure on the mask, and then lifting the mask off the substrate, such as by treatment in HF, to also lift off the unwanted portions of the LED layers overlying the mask. This procedure is then repeated for the green and blue LEDs, in succession. The sequence of steps is illustrated schematically in Figs. 4(a) through 4(d).

In fig. 4(a), an SiO_2 mask 200, having an aperture defining the desired area to be occupied by the red LED, is formed on the substrate surface 201, after which the layers forming the red LED, indicated in bulk as 202, are formed on the mask 200. The mask and the portions of layers 202 overlying the mask are then lifted off to leave red LED 203. A second mask 204 is then formed, as shown in Fig. 4(b), having an aperture defining

the area of the green LED, and the layers for the green LED, indicated as 206, are deposited on the second mask 204. The second mask is then lifted off, leaving blue LED 207. A third mask 208 is then deposited, as shown in Fig. 4(c), having an aperture defining the area of the green LED, and the layers 210 of the blue LED are deposited. The third mask 208 is then lifted off, leaving blue LED 211, to complete the wedding cake structure shown in Fig. 4(d).

Finally, the metallization is carried out to form the electrodes 108, 110, 112 and 114, as shown in Fig. 2, with the blocking layers 86 and 96 serving to confine the active areas of the red and green LEDs to the central regions of these LED structures.

A simple circuit for driving the multicolor LED of the invention is shown schematically in Fig. 5. In this circuit, the current through each LED is controlled by a high input impedance transistor. The circuit has first, second and third LEDs, each LED having an input and an output and having a different peak wavelength of light emission; first, second and third field effect transistors, one for each of the individual LEDs, each transistor having a source, a drain and a gate; first, second and third voltage inputs, V_B, V_G and V_R, one for each of the individual LEDs; a high voltage input V_H; a low voltage input V_L; and a ground; wherein the high voltage input V_H is connected to the sources of the first and third transistors S_1 and S_3, respectively; the first and third voltage inputs V_B and V_R are connected to the gates of the first and third transistors S_1 and S_3, respectively; the drain of the first transistor S_1 is connected to the input of the first (blue) LED; the drain of the third transistor S_3 is connected to the inputs of the second (green) and third (red) LEDs; the low voltage is connected to the source of the second transistor S_2; the second voltage input V_G is connected to the gate of the second transistor S_2; the drain of the second transistor S_2 is connected to the outputs of the first (blue) and second (green) LEDs; and the output of the third (red) LED is connected to ground. $V_H >> O$ and $V_L << 0$, for example, $-V_H = V_L$, while V_G, v_B and V_R depend on the transistor implementation. In the case of p channel MESFETs (metal semiconductor field effect transistor) for the blue and red LEDs and an n channel MESFET for the green LED as shown in Fig. 6, $0 < V_B$, V_R; $V_G < 0$, because the transistors are on when the gate voltage is zero.

A multicolor LED structure for use in such a circuit, including MESFET switches connected to V_H and V_L, is shown in Fig. 6. This multicolor LED structure is similar to the multicolor LED of Fig. 1, but is characterized by a greater difference in size of the individual LEDs than those of Fig. 1, in order to provide sufficient space on the top of each LED for both the electrode and a switch. Thus, similar elements have the same

reference numerals in Figs. 1 and 6, while the differences reside in the removal of the exposed portions of the contact layers 28 and 36, and a comparable area of the top contact layer 44, and the larger areas of exposure of the top cladding layers 26, 34 and 42 of the individual LEDs. These larger areas accommodate the additional electrodes 302, 306 and 310, formed on contact layers 304, 308 and 312, respectively. These contact layers 304, 308 and 312 are formed on the top cladding layers 26, 34 and 32 of the red, green and blue LEDs, respectively. In addition, an electrode 314 is formed on top cladding layer 42, adjacent electrode 310.

Electrodes 302 and 310, connected to V_H, are the sources for p-channel MESFETs S_1 and S_3, respectively, while contact layers 44 and 28 are the drains, and electrodes 314 and 48, connected to V_B and V_R, respectively, are the gates. Contact layer 36 is the source for n-channel MESFET S_2, while electrode 306, connected to V_L, is the drain, and electrode 50, connected to V_G, is the gate.

As will be appreciated, in this circuit, V_R, V_G and V_b are not directly representative of the red, green and blue components of a color display signal such as a video signal. That is because, as can be seen from Fig. 5, the currents I_R, I_G and I_b to the various LEDs are not directly controlled by V_R, V_G and V_b, but are a function of these voltages. This functional relationship may be expressed as follows:

$$I_B = f_1(V_B) \quad (1)$$

$$I_R + I_G = f_1(V_R) \quad (2)$$

$$I_G + I_B = f_2(V_G) \quad (3)$$

$$I_G = f_2(V_G) - f_1(V_B) \quad (4)$$

$$I_R = f_1(V_R) - f_2(V_G) + f_1(V_B) \quad (5)$$

Fig. 7 is a schematic diagram of a color display 700 comprising a two dimensional array of multicolor LED structures 702 of the invention, each structure 702 consisting of a red, a blue and a green light emitting LED 702a, 702b and 702c, respectively.

These structures 702 are arranged in rows and columns, between which are located column electrodes 704 and row electrodes 706, each column consisting of a triplet of V_R, V_G and V_B electrodes, and each row consisting of a doublet of V_H and V_L electrodes. An exemplary interconnection between structures 702 and the row and column electrodes is shown in the third row and third column, wherein red LED 702a is connected to V_H and V_R, green LED 702b is connected to V_L and V_G, and blue LED 702c is connected to V_H and V_B.

Such an array can be addressed a row at a time, in the conventional manner.

The invention has been described in terms of a limited number of embodiments. Other embodiments and variations of embodiments will become apparent to those skilled in the art, and are intended to be encompassed within the scope of the claims appended hereto.

For example, while the DH LED layer sequence for the three LED structure has been described in terms of n-p, p-n, n-p (or p-n, n-p, p-n), since this structure has certain advantages such as a minimal number of layers and external contacts, the sequence could also be: p-n, p-n, p-n (or n-p, n-p, n-p), which structure, while requiring more layers and external contacts, has the advantage of more independent operation of the individual LED's. Thus, where each LED has two external contacts, the operating voltages for each LED are completely independent of one another.

Claims:

1. A multicolor light emitting device (LED) structure comprising a stacked multilayer structure of a plurality of individual LEDs, each LED having a different peak wavelength of light emission, the multilayer structure comprised of a plurality of double heterostructure (DH) p-n or n-p LEDs, in which each LED is comprised of epitaxially grown layers of III-V compounds and in which the LEDs are formed as concentric cylindrical layers forming a wedding cake structure in which the top surface of each LED is at least partially exposed and in which electrodes are formed on the exposed top surface of each LED.

2. The multicolor LED structure of claim 1 in which there are three DH LEDs and in which each DH LED has an intrinsic active layer and the DH layers are in the sequence n-i-p, p-i-n, n-i-p; or p-i-n, n-i-p, p-i-n and in which the composition of the layers is: $In_xAl_yGa_{1-x-y}N$ and in which the device is grown on an at least partially transparent substrate which is selected from the group consisting of sapphire, SiC and ZnO.

3. The multicolor LED structure of claim 2 in which the relative intensity of light emitted from each LED is controlled by an external bias voltages applied to each LED and in which the three LEDs emit light in the primary colors red, blue and green, respectively, whereby control of the relative intensities of the primary colors results in a color within the gamut of the primary colors.

4. The multicolor LED structure of any of the preceding claims in which current blocking regions are formed in the LEDs below the top-most LED and below electrodes on the exposed top surface of the LEDs involved.

5. The multicolor LED structure of claim 4 in which the current blocking regions are formed by high-resistance regions obtained by ion implantation.

6. The multicolor LED structure of claim 4 in which the current blocking are formed by current blocking layers on top of the LEDs involved.

7. A multicolor display comprising an array of pixel elements, each pixel element consisting of a multicolor LED structure of any of the preceding claims and in which the pixels are driven in parallel by a dc voltage.

8. A driving circuit for the multicolor LED of any of claims 1-6, the circuit comprising: first, second and third LEDs, each LED having an input and an output and

having a different peak wavelength of light emission; first, second and third field effect transistors, one for each of the individual LEDs, each transistor having a source, a drain and a gate; first, second and third voltage inputs, one for each of the individual LEDs; a high voltage input; a low voltage input; and a ground; wherein: the high voltage input is connected to the sources of the first and third transistors, respectively; the first and third voltage inputs are connected to the gates of the first and third transistor, respectively; the drain of the first transistor is connected to the input of the first LED; the drain of the third transistor is connected to the inputs of the second and third LEDs; the low voltage is connected to the source of the second transistor; the second voltage input is connected to the gate of the second transistor; the drain of the second transistor is connected to the outputs of the first and second LEDs; and the output of the third LED is connected to ground.

9. A method of producing a multicolor light emitting device, the device comprising a stacked multilayer structure of a plurality of individual LEDs, each LED having a different peak wavelength of light emission, the method comprising the steps of:

(a) forming the layers corresponding to the individual LEDs sequentially on a substrate to form a multilayer structure;

(b) forming an etchant mask on the top surface of the multilayer structure;

(c) removing the exposed portions of the layers corresponding to the top-most LED by etching, to define the top-most LED;

(d) removing the etchant mask; and

(e) repeating the above steps for each of the succeeding LED structures, with the etchant mask for each repetition being progressively larger than that of the preceding mask, whereby the succeeding LED structures are progressly larger than the preceding LED structure, and in which method the LEDs are formed as concentric cylindrical layers, thereby to form a wedding cake structure in which the top surface of each LED is at least partially exposed and electrodes are formed on the exposed top surface of each LED.

10. A method of producing a multicolor light emitting device, the device comprising a stacked multilayer structure of a plurality of individual LEDs, each LED having a different peak wavelength of light emission, the method comprising the steps of:

(a) forming a mask on a substrate, the mask having an aperture defining the bottom LED;

(b) forming the layers corresponding to the bottom LED sequentially on the mask;

(c) removing the mask and the overlying portions of the layers to leave the bottom LED;

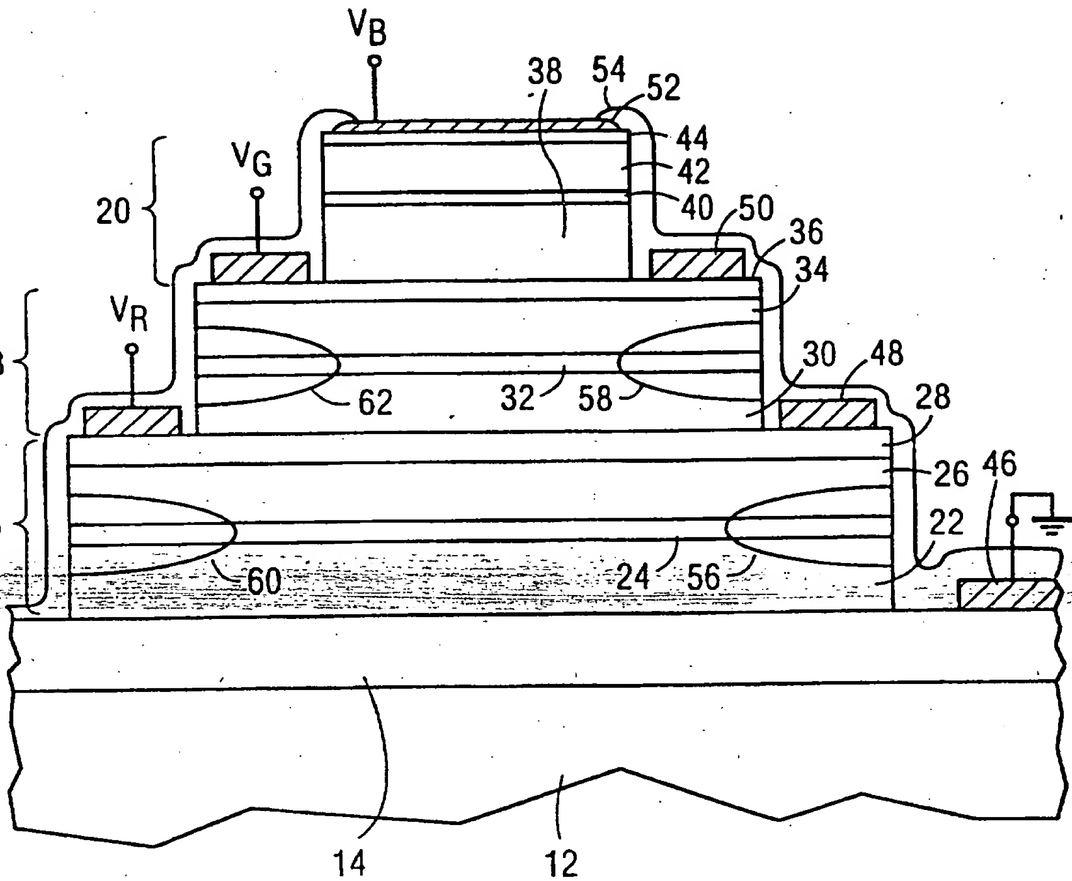
(d) repeating the above steps for each of the succeeding LED structures, with the mask aperture for each repetition being progressively smaller than that of the preceding mask, whereby the succeeding LED structures are progressly smaller than the preceding LED structure, and in which method the LEDs are formed as concentric cylindrical layers, thereby to form a wedding cake structure in which the top surface of each LED is at least partially exposed and electrodes are formed on the exposed top surface of each LED.

11. The method of claim 9 or 10 in which current blocking regions are formed in the LEDs below the top-most LED.

12. The method of claim 11 in which the current blocking regions are formed by ion implantation after formation of the multicolor LED structure.

13. The method of claim 11 in which the current blocking regions are formed by forming current blocking layers during formation of the multilayer structure and in which the current blocking layers are selectively etched to remove central portions and leave peripheral portions of such layers.

14. The method of claim 13 in which each LED structure comprises a first cladding layer, an active layer, a second cladding layer and a transition layer, and the current blocking layers are formed on top of the second cladding layers.



V_B
38
54
52
44
42
40
50
36
34
20
V_G
18
V_R
30
48
28
62
32
58
26
46
16
22
60
24
56
14
12

FIG. 1

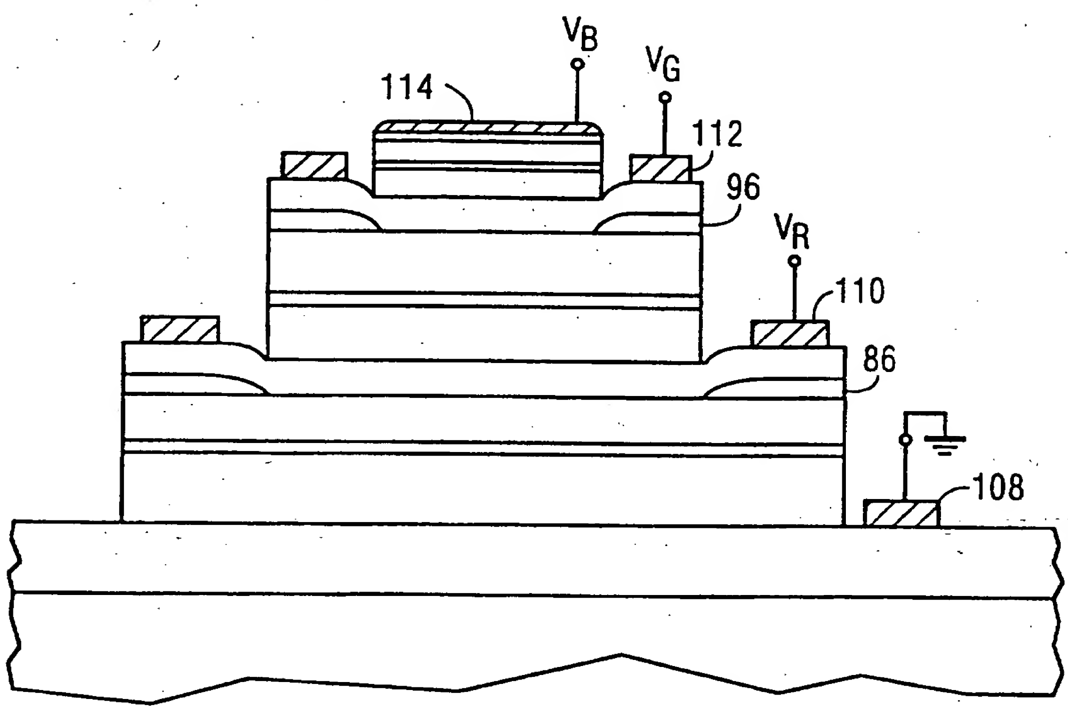


FIG. 2

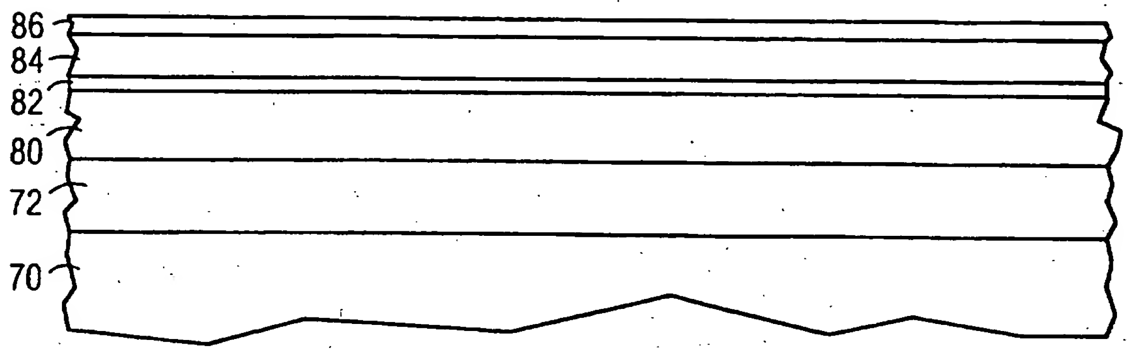


FIG. 3A

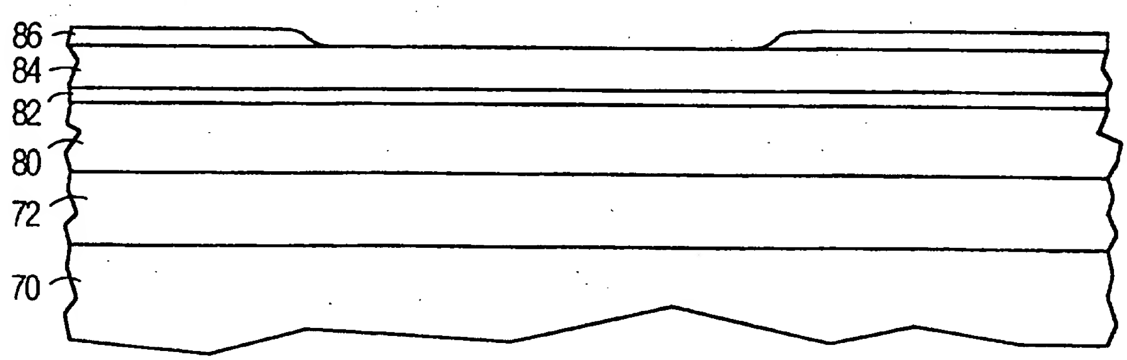


FIG. 3B

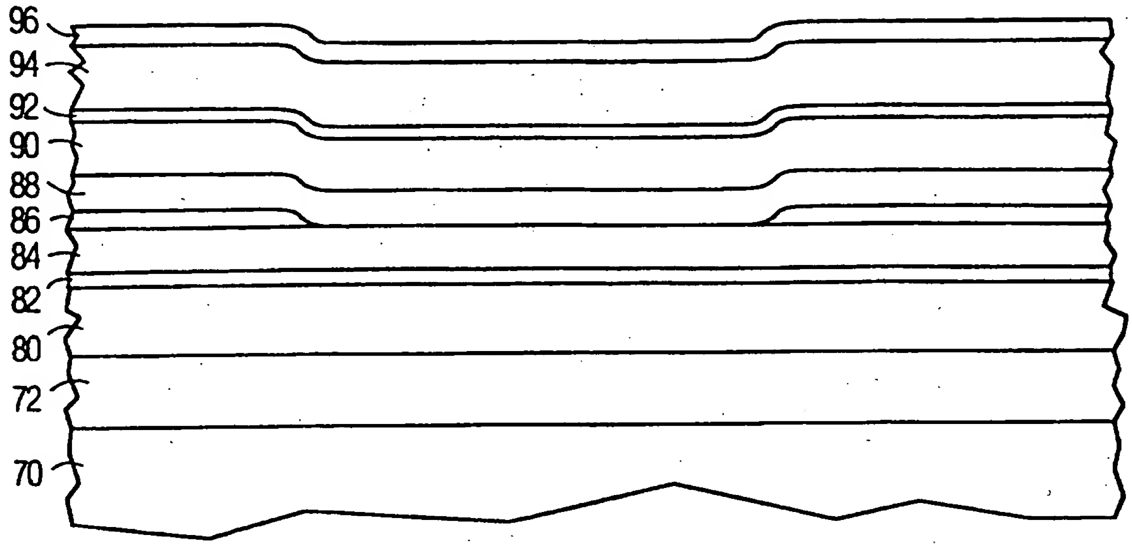


FIG. 3C

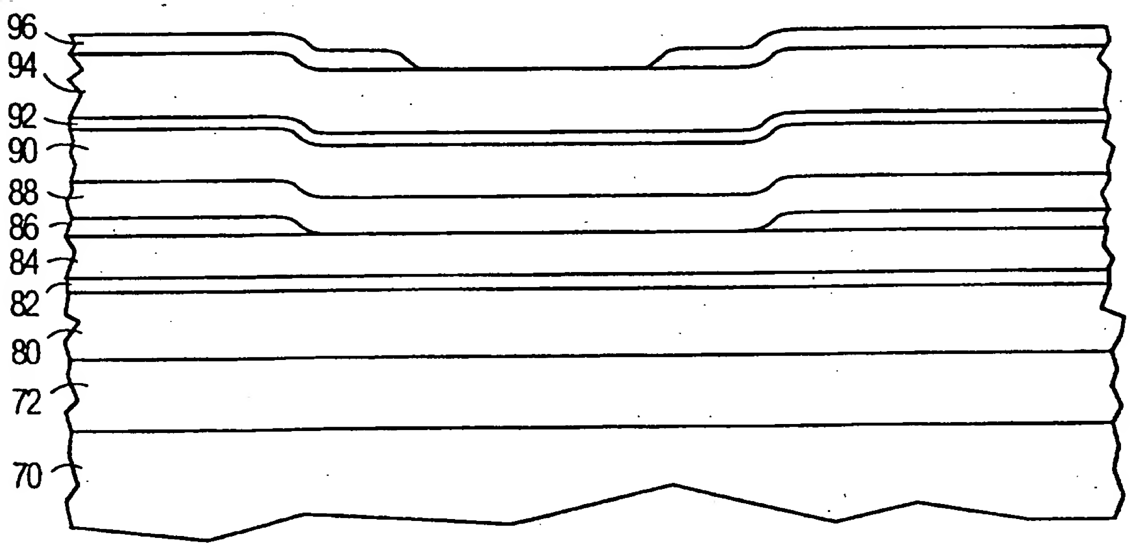


FIG. 3D

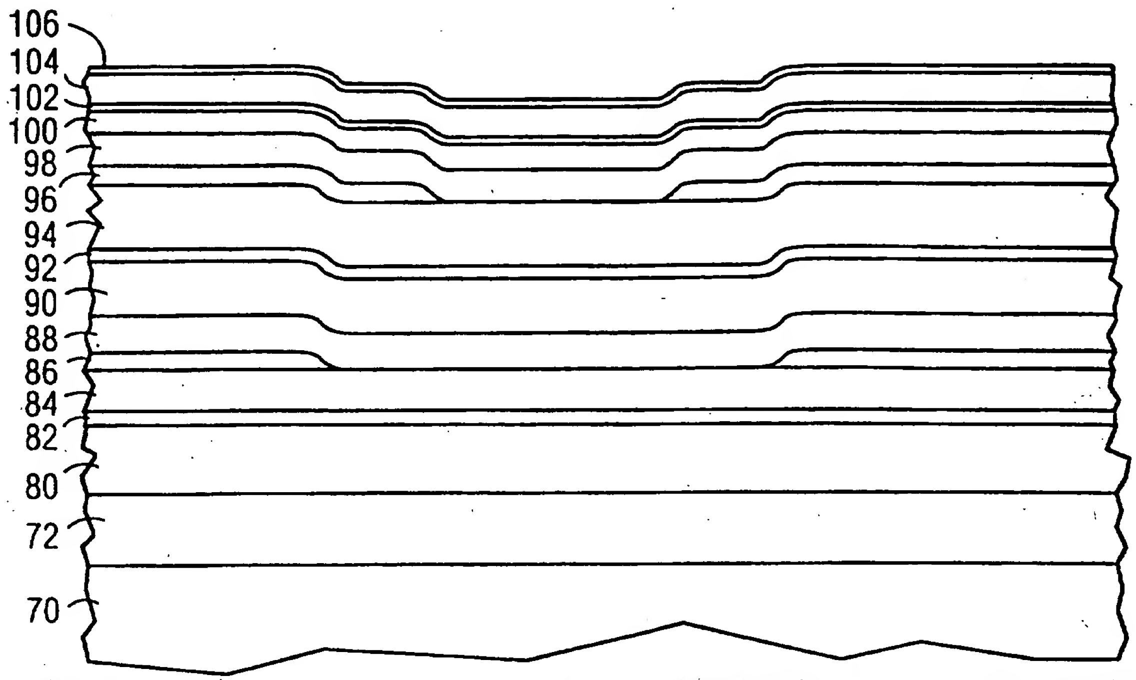

106
104
102
100
98
96
94
92
90
88
86
84
82
80
72
70

FIG. 3E

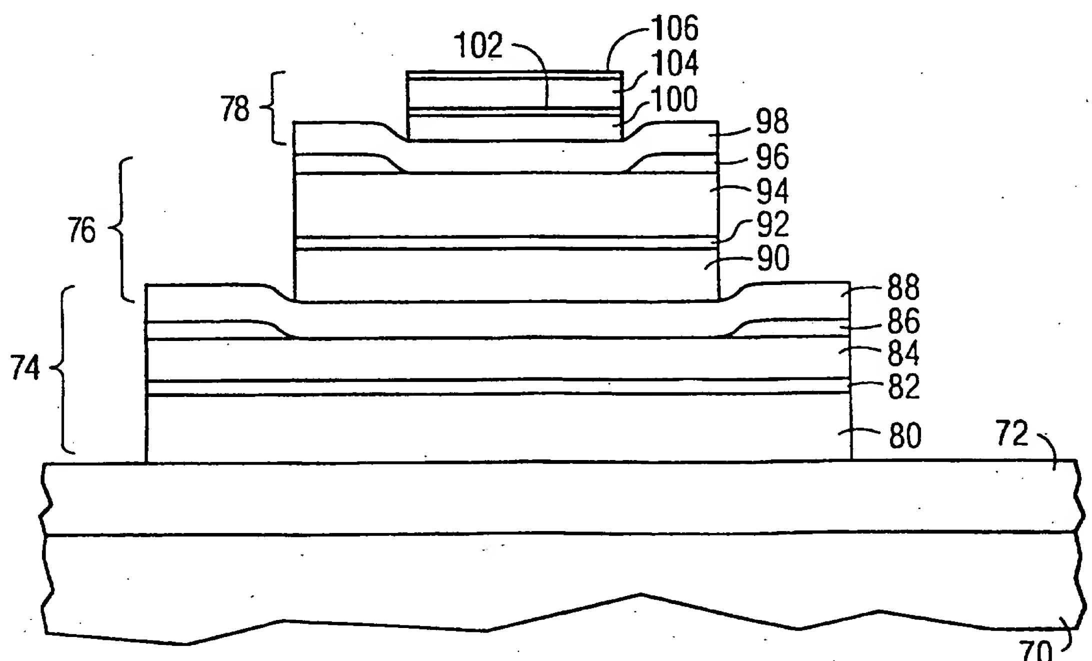

102
106
104
100
78
98
96
94
76
92
90
88
86
74
84
82
80
72
70

FIG. 3F

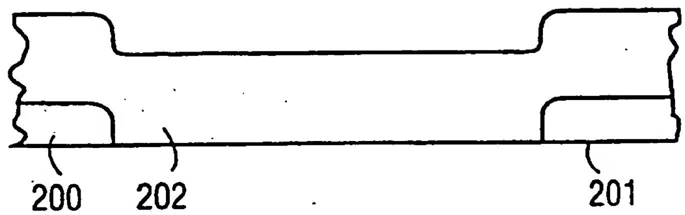


FIG. 4A

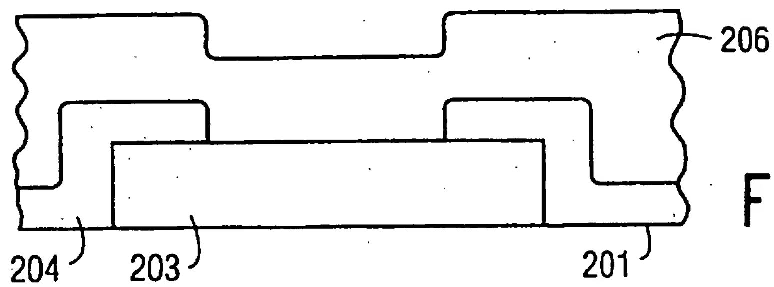


FIG. 4B

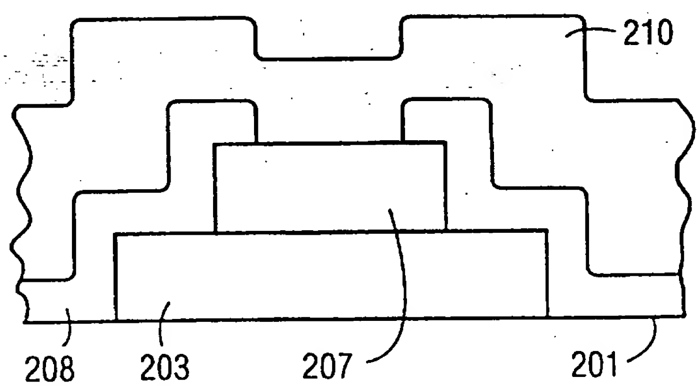


FIG. 4C

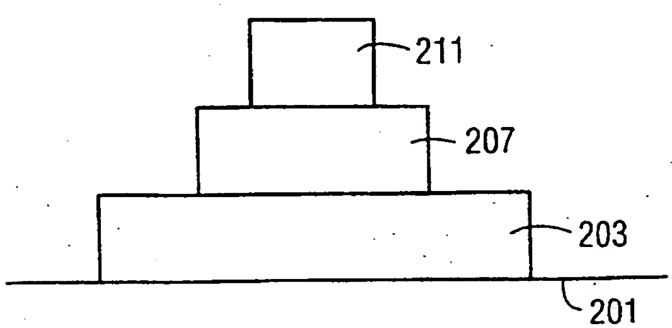
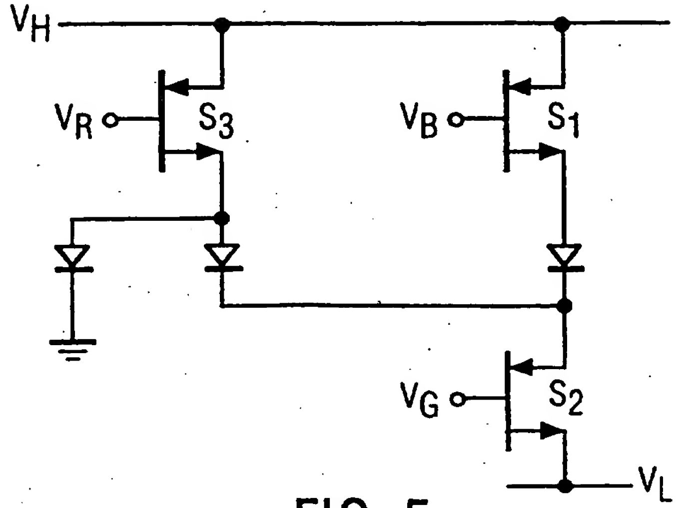
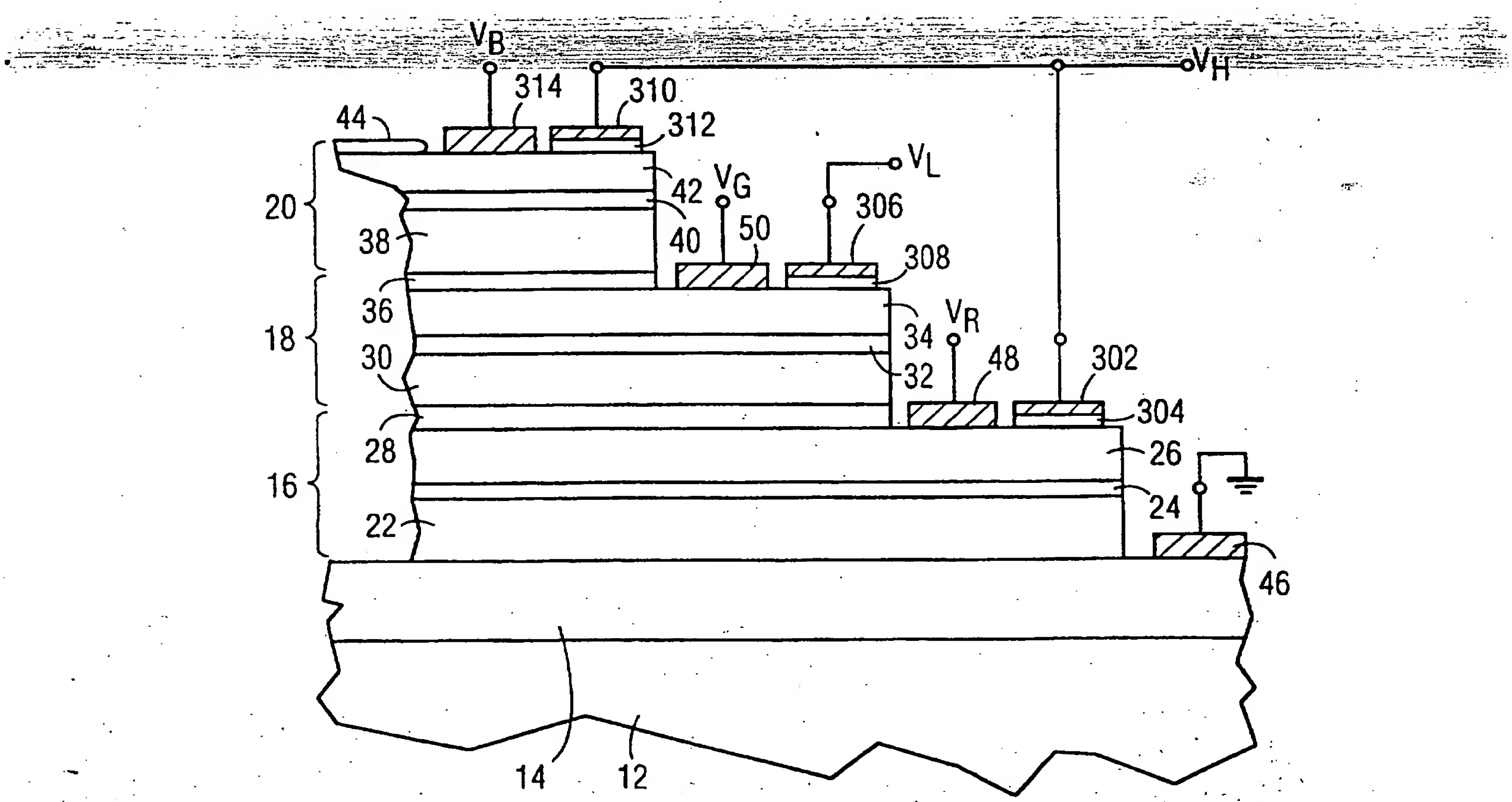


FIG. 4D



V_H
V_R
S_3
V_B
S_1
V_G
S_2
V_L

FIG. 5



V_B
V_H
314
310
312
44
20
42
V_G
V_L
40
50
306
308
38
36
18
34
V_R
30
32
48
302
304
28
26
16
24
22
46
14
12

FIG. 6

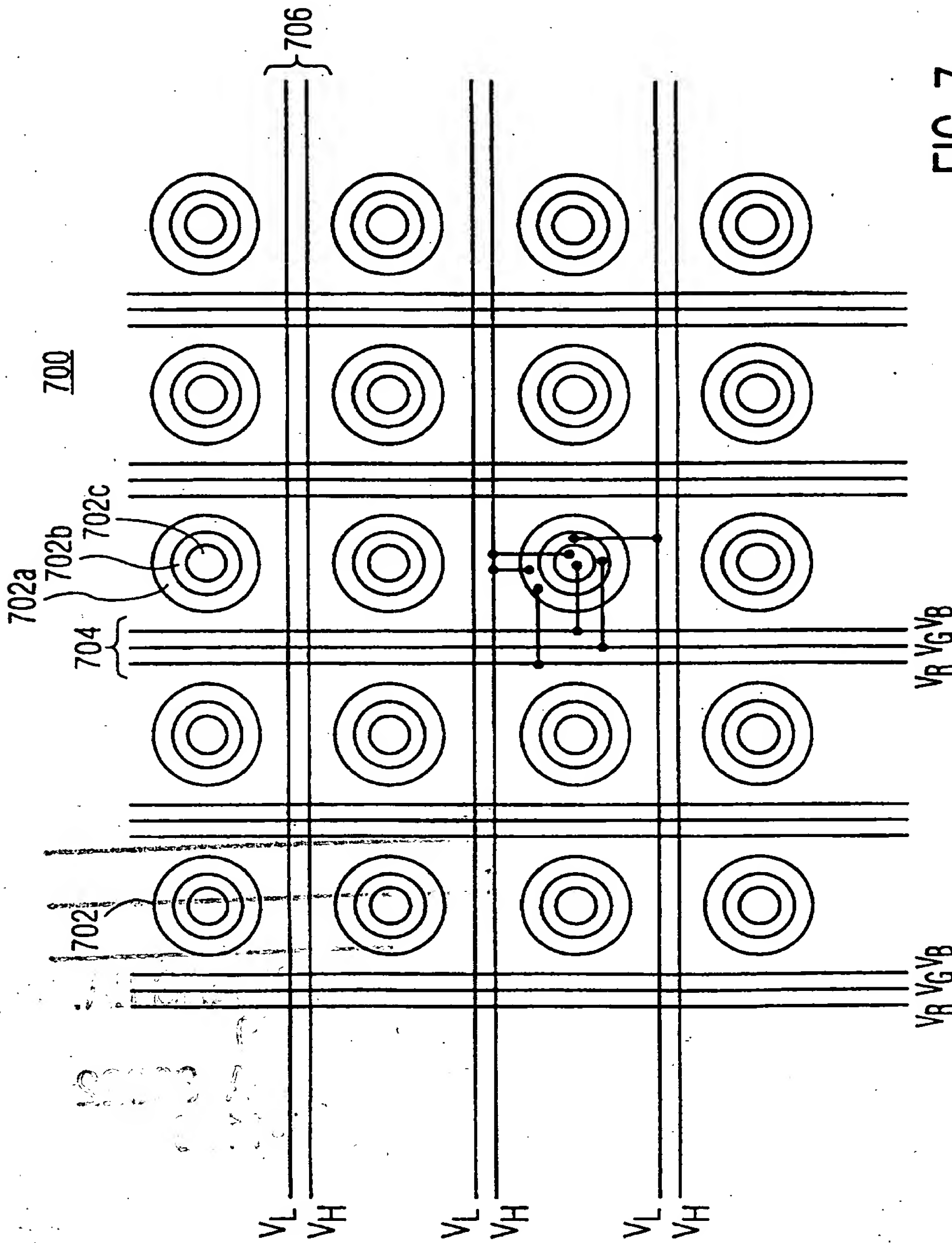


FIG. 7